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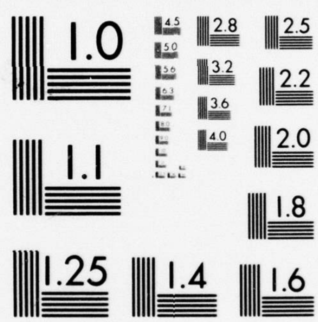
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Applications of Decision Analysis to Occupational Health and Safety Problems

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This report presents an evaluation of the methodologies of decision analysis as aids in managing the occupational health and safety activities of an organization. Various techniques from the field of decision analysis are evaluated in terms of the philosophical and technical difficulties that might be encountered in a real-world application in this problem area.

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Table of Contents

Applications of Decision Analysis to Occupational Health and Safety Problems

1. Introduction

This report evaluates several decision analysis techniques as potential aids in managing the occupational health and safety activities of the United States Navy. We begin with a brief review of the problems and issues related to occupational health and safety and identify some of the reasons that this area is becoming increasingly important in the United States Navy and in private enterprise as well. The forces and pressures that have generated a broad concern with occupational health and safety must be well understood in order to evaluate the suitability of alternative tools of analysis.

Next we shall consider the role of analysis in occupational health and safety decisions. Analysis may take place at two levels. First, policy formulation at the national level or for the United States Navy is extremely difficult, since the impacts of these policies on workers, on citizens living in close proximity to a potentially hazardous workplace, and on costs must all be considered. In the context of these exceedingly complex issues, formal methods of analysis may have a limited but useful role. Second, at an operational level, analysis may be used to identify the most effective means of implementing general policies. The tools of analysis that are the most appropriate at the policy and operational levels may differ.

We were motivated to explore the possibility of broadening the applications of decision analysis in the area of occupational health and

safety, since the problems that naturally arise in this area exhibit the characteristics of problems that have been successfully analyzed with these approaches. That is, they involve risk, since the outcomes from the various alternative decisions cannot all be predicted with certainty. In fact, the problem of determining the probability that an outcome may occur may be a difficult task by itself. The outcomes are often multidimensional, and are not easily collapsed into a single figure of merit, such as dollars. Finally, it may be necessary to consider the views and values of several interest groups in the final choice among the alternatives. These characteristics indicate that the methodologies of decision analysis may play a useful role in aiding the decision maker(s) to choose among alternatives.

In order to illustrate some of the difficulties associated with performing analytical studies in this area, we shall critically examine some of the cost/benefit studies that have been undertaken. As we shall see, traditional cost/benefit analysis can be viewed as a special case of one of the techniques of decision analysis, the theory of collective choice. Therefore, the objections to these studies and their limitations will provide a basis for evaluationg the potential contributions of decision analysis.

The term "decision analysis" is used to include more specific topics such as risk analysis, multiattribute utility theory, and the various theories of collective choice. For each of these topics, we shall give a brief summary of the approach and a review of its application to problems of occupational health and safety or to related fields. Next, we provide a hypothetical example of how this tool might be applied to a specific

problem, the exposure of workers and others to asbestos fibers. This context has been selected for illustrative purposes in order to provide a concrete setting for the examples. Finally, we give a critique of each technique of analysis in terms of the philosophical and technical difficulties that might be encountered in a real-world application.

2. Problems and Issues

2.1 The Reasons for Concern

We assume that all organizations are morally committed to the reduction of occupational risks to as low a level as is practical. However, there is considerable controversy regarding the level of risk that is "low enough" and the concept of what actions are "practical".

Even the term "risk" is an ambiguous one, and we will use it with several meanings in this report. In some contexts, "risk" will refer to the probability that death, illness, or injury may occur for a specific individual. In other contexts, "risk" may mean an estimate of the number of persons who are expected to die if an accident occurs. In its most general sense, a "risky" decision is one where the outcome associated with an alternative is not known with certainty. To avoid repetitive definitions or the introduction of new terminology, we will assume that the reader can infer the appropriate interpretation of this term from the context of the discussion.

The notion that some risk is necessarily inherent in some occupations is an acceptable one in our society. Certainly, many of the occupations within the modern, high-technology United States Navy involve a relatively high exposure to risk even in times of world peace. Some risks are obvious, such as the ones faced by the pilot of an aircraft launched from a modern

carrier. Other risks are perhaps less obvious, but may involve even greater hazards. Many servicemen may be exposed to toxic chemicals that are required for aircraft and rocket fuels, and to low levels of radiation from atomic weapons and propulsions systems. In some cases, the risk associated with these exposures may only be recognized years later. For example, the tragic effects of asbestos in contributing to lung cancer were established only after many workers had contracted the dread disease and thousands of others had been exposed. Currently, many of the more than 300,000 civilian employees of the United States Navy experience some exposure to asbestos or to other potentially harmful substances.

While the issue of occupational health and safety has always been a serious matter for concern, the topic seems to be receiving an increasing amount of attention today. There are several possible explanations for this, and perhaps the simultaneous interaction of one or more is responsible for the heightened interest.

From 1960 to 1970 the rate of accidents in manufacturing rose by 26.7 percent, reversing a long-term downward trend in the accident rate. Some of this increase in accident rates can be explained by cyclical variations, but it was used as evidence of an "on-the-job health and safety crisis" by the House Committee on Education and Labor. Concern over work-related disease is also growing. A recent front-page headline in the Austin American-Statesman (9/12/78) stated, "National Study Links 20% of Cancer to Jobs." According to the story, HEW Secretary Joseph Califano told an AFL-CIO conference that even this figure may be conservative. He also identified the exposure of 4.5 million workers to asbestos in the World War II ship yards as a major contributor to this problem, and said

that asbestos may be responsible for 10 to 15 percent of all cancer deaths in the United States each year. Eventually, a total of 1.6 million deaths may be attributed to asbestos exposure.

At the same time, changes within our society may have generated some of the increased concern over occupational health and safety. The increased affluence and educational levels of workers have probably made many of them more aware of the hazards of some occupations, and less willing to tolerate these hazards since they are more secure financially and have more job opportunities. In the early days of the industrial revolution and during the years of the Great Depression, a worker faced with a choice between a hazardous job and no job at all would often feel fortunate to accept even a risky job opportunity. Increased awareness and mobility makes today's worker much more selective. Labor unions may have also played an important role in increasing the pressure for safer and healthier working conditions.

The last two decades have also seen the government expanding its role as a protector of the citizens. In the late 1960's, there was a flurry of legislation regarding coal-mine health and safety, air pollution, consumer-product safety, and automobile safety. Mandatory seat belts, helmets for motorcycle riders, no-fault insurance, and reflectors on bicycles are all recent manifestations of a social value that requires individuals to be protected from the careless actions of others and from themselves.

In occupational health and safety, a worker at the turn of the century would be required to show that his employer was at fault in order to be compensated for an injury. Workman's compensation became a form of "no-fault" insurance for workers that provided compensation for injuries that were not necessarily the result of the employer's actions. The more recent OSH Act goes even further by directly regulating the workplace itself.

As we shall see, these trends and their philosophical underpinnings should be understood since they may be the basis for sharp criticisms of analytical studies in the area of occupational health and safety.

2.2 The Actors

The problem of managing occupational health and safety can be better understood when the important actors who influence decisions are identified. There are several ways of categorizing actors, including the following:

1. employers - U.S. Navy, contractors
2. employees - individuals, unions, families, and individuals subject to involuntary risks
3. consumers - general public, taxpayers, purchasers of a product
4. regulatory groups - U.S. Government, OSHA, NIOSH, courts
5. experts - researchers, doctors, engineers
6. opinion makers - media

Each of these groups may attempt to influence health and safety decisions. Any technique of analysis should be used with full knowledge that it may be subject to criticism from each group. These criticisms may focus on disagreements about facts among the "experts", or on more basic philosophical issues raised by representatives of the employees, the regulatory groups, or the consumers. Almost any analytical approach to problem solving involves some implicit or explicit simplifying assumptions. Since each of these assumptions may be attacked by individuals from some group, it is perhaps understandable that previous efforts involving quantitative analysis have had only minor impacts on decisions.

Briefly, we identify each of these actor groups in more detail, and describe some of their objectives and concerns with regard to occupational health and safety policies.

2.2.1 Employers. The employers of interest in this report are the United States Navy and its contractors. We assume that both would normally adopt a responsible position toward occupational safety and health issues. Beyond the strong moral commitment to health and safety, an employer is motivated to provide a hospitable workplace in order to minimize the costs of workman's compensation and working days lost because of occupation related diseases or injuries. Employers would also like to avoid the critical attention of regulatory groups and opinion makers that might result from a serious incident.

2.2.2 Employees. We consider the employees both as individuals and as union groups. For simplicity, we also include the families of employees within this group and those individuals subject to involuntary risks due to work-related activities. The latter would include individuals residing in close proximity to potential hazards. These hazards, such as explosives and LNG storage tanks, may effect a wide geographical area.

The employees would like to be guaranteed a completely safe, healthy environment at no personal cost, in either dollars or inconvenience. As an alternative, they would expect a "risk premium" in wages for hazards that cannot be avoided.

2.2.3 Consumers. The consumers in our study are the taxpayers who finance the United States Navy and benefit from its protection. They expect this service to be provided efficiently, with no extravagant programs. They also provide a social conscience that may influence the other actors.

2.2.4 Regulatory groups. Several regulatory groups are active in occupational health and safety. The most obvious is OSHA, the Occupational Safety and Health Administration, that regulates the activities of the private contractors of the United States Navy. The objective stated by Congress for OSHA was "to assure so far as possible every working man and woman in the nation safe and healthful working conditions." There is considerable debate about whether the phrase "so far as possible" should be interpreted as "so far as practical." For assessments and a discussion of OSHA, see Nichols and Zeckhauser [1977], MacAvoy [1977], or Smith [1976].

In addition to its stated goal, a regulatory agency will naturally attempt to develop regulations that are easy to manage (implement and control) and that are consistent with the existing legal framework. Regulations that are easy to manage may not be most effective, and vice versa.

Although not subject to direct regulation by OSHA, the United States Navy must be sensitive to its activities. If serious injuries resulted from practices blatantly in disregard of OSHA regulations, pressures for increased regulation of Navy activities would build. Congress can exert pressure on the Navy directly or indirectly through budget appropriations.

The courts also tend to regulate activities directly or indirectly. The possibility of litigation in a civil suit may influence the activity of an employer.

2.2.5 Experts. Although not necessarily affiliated with any other group, some "experts" may have a significant influence on policies. For example, the research activities of Dr. Irving Selikoff of Mt. Sinai Hospital in New York have had an enormous impact on concern over the hazards of exposure to asbestos. The tragic effects of asbestos have

also created concern over other potential carcinogens, and perhaps have influenced OSHA to adopt an extremely conservative position in this area.

2.2.6 Opinion makers. Finally, the opinion makers can influence policies by focusing attention on problems of occupational health and safety. Television programs or newspaper stories dramatizing the unfortunate effects of occupation-related injuries or diseases can create public awareness of problems and increase pressures on regulatory groups to take actions.

Opinion makers are motivated by a desire to reach large audiences. Unfortunately, this may tempt them to "sensationalize" stories in an attempt to create wider interest. At times, this may distort public opinion and the pressures on regulatory agencies.

2.3 From a Market System to Regulation

A complete review of the changing policies in occupational health and safety is beyond our scope. A notable reference in this area is the work of Chelius [1977], where a history of accident liability law is given.

In brief, prior to 1911 the issue of occupational health and safety was regulated through the courts and the labor market system. Under this system, the employer had "...an affirmative obligation to eliminate unreasonable risks that were obvious and to make reasonable inspections in order to uncover and remove unreasonable hazards that were not ....a calculus was devised wherein the degree of care to be exercised was measured by balancing the magnitude of the risk and the likelihood that it would cause injury against the burden of avoiding the risk" (Miller [1974]) Under this system, the employer was not responsible for compensating the employee for injuries that resulted from the employee's own negligence.

The courts recognized that some occupations were inherently more risky than others, but as long as the employer took reasonable precautions, he was not liable for the accidents that occurred. Under this system, the labor market was assumed to ensure that workers who accepted relatively more risky jobs received a wage differential as compensation. The reliance on the "market system" is still in favor with many economists, as we shall see.

Beginning in 1911, the states started to enact workman's compensation laws which require an employer to compensate an injured worker regardless of the cause of the work injury. This payment, however, is generally less than the full cost of the accident to the worker, and considerably less than the worker might obtain in a civil suit if he could demonstrate that the employer was at fault. In a sense, workman's compensation may be viewed as a form of no-fault insurance.

One criticism of workman's compensation is that this system reduced the incentive for employers to provide a safe workplace, since their payment to the worker did not increase significantly if the injury was the employer's fault. The rising accident rate in the 1960's coupled with other pressures led to the passing of the Occupational Safety and Health Act (OSH Act) of 1970. The objective of this act is "to assure so far as possible every working man and woman in the nation safe and healthful working conditions." This objective is to be accomplished by direct regulation of the workplace.

Economists like Smith [1976], Oi [1974], and Nichols and Zeckhauser [1977] criticize direct regulation as the means of implementing public policy in this area. They would prefer more reliance on incentives and the labor market.

Calabresi [1970] argues that the free market may not be able to adequately deter accidents for the following reasons:

1. Adequate market determination of accident costs requires freedom on the part of victims to refuse the bargain and avoid the risk of injury. Lack of mobility and adequate alternatives may restrict the labor markets.

2. Free market determination of the value of accident costs will be acceptable only if the potential injuries and victims are aware of and consider the risks. Individuals may not be able to obtain adequate knowledge about risks; they may not view themselves as potentially the actual victims; they may choose short run payoffs now and regret it later; they may not be the only ones to bear the costs of accidents.

3. Statistical willingness to take risks does not give an adequate value of what an accident costs if it actually takes place. These arguments apply to health hazards as well, and can be used to defend the use of direct regulation of industry by OSHA.

MacAvoy [1977] reports an evaluation of OSHA safety regulations by a Presidential Task Force. The Task Force is critical of the existing OSHA standards, but generally accepts the notion of regulation by standards. They do recommend a performance oriented approach to writing standards that provides more flexibility for the response of an employer. Thus, it seems likely that OSHA will continue to be a major regulatory force in occupational health and safety, but there are some indications that these regulations may become more flexible, and leave the employer some discretion regarding the most appropriate way to comply. This increased flexibility will stimulate the need for new tools of analysis to assist in choosing among the alternative means of compliance.

3. The Role of Analysis

3.1 The Need for Analysis

In the context of the legal, market, social, and political forces that have interacted to created the existing system for managing occupational health and safety, is there a legitimate need for the formal analysis of of problems? That is, will the existing decision making processes within the government or the United States Navy be influenced by the results of a formal analytical study?

In particular, we are concerned with a formal application of decision analysis to these problems. The process of decision analysis requires the following steps:

1. Problem definition: A thoughtful analysis of the boundaries of the problem, and the identification of the alternative decisions that might be made.

2. Structuring: This step requires the identification of the different outcomes that might occur if each alternative were selected, and of the events that will determine which outcome will actually occur. Often the problem structure may be represented as a decision tree.

3. Estimation of probabilities: Probabilities must be assigned to the various events. These probabilities may be based on historical data, or be elicited subjectively from individuals.

4. Assignment of value: A value must be assigned to each outcome. This task can become quite complicated when there is no natural figure of merit, such as money, when the outcomes are multi-dimensional, and when several interest groups disagree over the appropriate values.

5. Calculation: The alternatives are ranked by multiplying the event probabilities times the outcome values in a sequence determined by

the problem structure.

The current deicision-making processes that have evolved in occupational health and safety avoid these steps. The difficulty seems to be that there is no _objective_ basis for carrying out these steps in the context of these problems. By "objective" we mean a process that will lead to a decision exclusively on the basis of scientific _facts_.

For example, the proposed policy for the regulation of carcinogenic air pollutants by OSHA (Register [1978]) classifies toxic substances into three categories: non carcinogen, potential carcinogen, and known carcinogen. The distinction among these categories is based on "objective," scientific data from animal studies or from epidemological studies, if available. _If_ a substance is found to cause tumors in two distinct species of laboratory animals, even at an extremely high dose level, then it is classified as a known carcinogen, and it must be handled in the workplace by a standard set of regulations.

Implicitly, these animal tests are interpreted as indicating that the probability that a substance is a carcinogen is greater than 0. There is no attempt to continue with Step 3 of the decision analysis framework and actually estimate the probabilities that exposure to this substance at different levels of concentration would cause tumors in man. Evidently, this step would be considered too controversial. Further, there is no attempt to explicitly value the likely outcomes from this exposure, by systematically trading off the costs of regulation against their effects on the probability of deaths or other adverse health effects among the workers.

Thus, the stumbling blocks to the application of decision analysis are Step 3 when historical data are not available and Step 4. Both of these steps require the introductive of subjective values into the analysis.

Once we recognize that subjective values must be used as the basis for a decision, then we must also recognize that reasonable men can legitimately disagree about the final decision itself. From OSHA's standpoint, this is currently an unacceptable result. They evidently feel compelled to develop a process of regulatory decision making that has the appearance of objectivity. In the highly political arena in which they must function, this may be a rational position for them to take, but it may not lead to the most socially desirable set of occupational health and safety regulations.

Further, OSHA seems aware of this problem. The notice of the public meeting to discuss the proposed regulatory policy for carcenogenic air pollutants includes the following statement:

> In determining the appropriate degree of control, to what extent should each of the following factors be considered: the risk caused, the benefits conferred, the availability of substitutes and the costs of control? Should these factors be balanced against each other, and if so, how? (Register [1978]).

We interpret this remark as a challenge that OSHA does not expect to be met by any objective decision making process, and they seem likely to reject a subjective one at this time.

In response, the American Industrial Health Council (AIHC) has criticized the OSHA proposal because of the failure to allow for trade-offs in determination of the regulatory response (American Industrial Health Council [1978]). The AIHC suggests that "...OSHA should develop regulatory priorities based on such matters as the strength of the evidence implicating the chemical as a carcinogen, the carcinogenic potency of a chemical, the number of employees exposed, the extent of exposure, and the likelihood of a carcinogenic event." (AIHC [1978, p. 15]). However, AIHC fails to suggest just how the tradeoffs among these factors might be made.

Eventually, it does seem that these issues will have to be faced explicitly. The opening remarks of Dr. Eula Bingham of OSHA to the International Conference on Public Control of Environmental Health Hazards in June 1978 contained the following statement:

> ...there are very few government health regulations--such as a tougher OSHA asbestos standard or the new cotton dust standard which we recently promulgated -- which do not cause increased costs of production; these are commonly passed on to consumers in the form of inflationary price increases. As evidenced by the White House debate surrounding the cotton dust standard several weeks ago, this administration is sincerely determined to provide the greatest amount of worker protection while minimizing the inflationary effects of such regulation and avoiding unnecessary burdens on owners and employers.

To be of use in addressing these problems, an analysis tool would have to treat nonmonetary outcomes such as the risk of death or injury and a change in the rate of inflation. It would have to provide a means of examining unequal impacts of alternative policies on different interest groups. It should also be neutral in terms of its underlying assumptions and philosophy. Finally, it should be easy to implement, to understand, and to explain.

To illustrate the difficulties that are encountered by the introduction of analytical techniques in this area, we shall critically review some applications of economic theory to policy problems that may alter human mortality. Our interest in this issue is twofold. First, we are interested in the role of economic analysis for its own sake. Second, as we shall discuss in Section 4, economic (cost/benefit) analysis may be viewed as an important special case of decision analysis. Therefore, some of the criticisms of this approach may also be relevant for other techniques of decision analysis.

3.2 Economic (Cost/Benefit) Analysis

The technique of cost/benefit analysis has been used to analyze several issues related to occupational safety and health. Oi [1973a, 1973b, 1974] has provided an economic theory for dealing with safety as one of the unavoidable joint products of any enterprise.

The theoretical and conceptual basis for cost/benefit analysis is the following statement: we should seek to minimize the sum of occupational accident and disease costs, and the cost of preventing these accidents and diseases. This statement leads to the seemingly obvious conclusion that we should not spend more to reduce disease and accidents than they cost. As we shall see, however, the implementation of this notion is subject to serious criticism on several grounds.

Hirshleifer, Bergstrom, and Rappaport [1974] provide a discussion of the use of cost/benefit analysis to evaluate projects that may alter human mortality. We paraphrase their presentation as follows: The general premise of cost/benefit analysis is that public policy should be determined by a systematic comparison of favorable and unfavorable impacts as valued by the individuals upon whom the impacts fall.

More specifically, these favorable and unfavorable impacts must be valued by the efficiency criterion, meaning that costs and benefits must be measured in terms of the market evaluations of goods and services produced or foregone. Two essential aspects of the efficiency criterion are : (1) Aggregation: summation of the values of all consequences, regardless of to whom they accrue and (2) Use of market values: measuring consequences by the weights assigned in the market (or, in terms of inferred or implicit market values).

Both of these criteria are the basis for criticism of cost/benefit analysis, especially when the methodology is applied to the evaluation of projects that affect human mortality. The aggregation principle implies that a dollar of benefit (or cost) to one person is counted equally with a dollar of benefit (or cost) to another. But suppose the benefits of a project accrue to the rich, while the costs accrue to the poor. This aggregation criterion would hardly be politically acceptable as a basis for a decision. Aggregation would be even more sharply criticized if the benefits of a project are monetary returns to the rich, while the costs represent the market value of the lives lost among low income workers.

Hirshleifer et al defend the aggregation criterion on several grounds. First, this rule will increase the size of the total economic pie. The redistribution of these returns can be a separate decision for policy makers. Second, there are many such projects to be evaluated, and some may benefit the rich, but others will benefit the poor. As long as we follow the efficiency criterion, everyone will be better off in the long run.

We find these arguments somewhat persuasive when discussing projects where the benefits and costs are primarily economic, such as in a water control project, or where the benefits are evenly spread, as in the case of national defense. However, the basis for the simple use of aggregation falters when the costs include the loss of human life. The knowledge that the economic benefits of a project may be redistributed later by the tax system would seem to provide little comfort to individuals subjected to risk, or who actually die.

The market value criterion also can be defended as the appropriate basis for many decisions. Hirshleifer et al note that the market value of a commodity represents a kind of social consensus as to the worth of a unit change in the amount of a product or resource.

Again, the market value criterion seems appealing for the evaluation of many public projects that do not affect human mortality. When human lives are at stake, however, we are confronted with both operational and philosophical difficulties in applying this criterion.

From an operational standpoint, there is no obvious market place for human life to use in determining its value. Oi [1973b] notes that the slave markets in the pre-Civil War South provide information on the market value of a disabling injury. Quoting from a study by Fogel and Engerman, he states:

> Some preliminary estimates indicate, for example, that the market price of a slave with one arm was approximately 25 percent of the market value of a healthy, uninjured male slave. Since the market value will in equilibrium, be equal to the present value of the slave's net marginal product, and since roughly 40 percent of a slave's marginal product was required for his maintenance, the 25-percent figure implies that the loss of an arm led to a 45 percent reduction in his marginal productivity as a field hand...It will be interesting to compare the data being assembled by Fogel and Engerman with with the schedules of compensation under workmen's compensation laws [Oi, 1973b].

Perhaps these comments are only meant to be curious academic speculation, but their presence in a serious study on the economic theory of occupational health and safety certainly helps to explain why many labor leaders and some academicians are strongly opposed to the use of cost/benefit studies as the basis for policy decisions in this area.

In order to impute a market value for human life, several early cost/benefit studies were based on the use of the net present value of the income lost by a deceased individual. Such measures obviously rewarded projects designed to save college-educated white males in their middle twenties,

while penalizing those for the elderly, housewives, underprivileged minorities, and small children. On a philosophical basis, many people would object to valuing one individual's life over another on the basis of his income. Rhoads [1978] and others have noted that this approach is inappropriate for policy making.

The method for obtaining an estimate of the value of a human life that is currently in favor among economists is the "willingness to pay" approach. The idea is to determine how much an individual would be willing to pay to reduce the probability of his being killed, and use this result to determine the value of a human life. For example, if 1000 workers in an occupation associated with an extra death risk of 0.001 per year will each sacrifice $200 per year to reduce this extra death threat to 0.0, then the implied value of a human life is $200,000.

Since economists strongly believe in using "scientific" data obtained from the market, they have attempted to measure willingness to pay by comparing salaries in risky occupations with those in relatively safe ones. A statistical study by Thaler and Rosen [1973] used this approach to estimate that workers are, in fact, willing to pay $200,000 to save a life. Using the same strategy with a different data base, Smith [1976] obtained a value of $2.6 million, which differs from the earlier estimate by a factor of thirteen.

The difficulty of applying results from studies that produce such large discrepancies should be obvious. Beyond the practical problem of

empirically estimating willingness to pay, there are some additional difficulties with this approach. Calabresi [1968] and others have argued that workers do not know the real differences in risk between jobs, and could not act rationally on this information even if it were known. With regard to the first point, even most "risky" occupations are sufficiently safe so that workers seldom observe actual incidents of injury or occupationally related disease (black lung disease among coal miners is a notable exception). Thus, they do not have sufficient information to distinguish between jobs with different injury or death rates at the third decimal place.

Another difficulty with this approach is that it assumes that the value of a reduction in risk by 0.001 is independent of the initial level of risk. As Raiffa [1968] and Kahneman and Tversky [1978] point out, this will not necessarily be the case. They argue, in fact, that the reduction of 0.001 should be valued more highly when the initial level of risk is high than when it is low. This creates some difficulty in interpreting the results of these studies as implying a value for a human life.

Even if the risk data were well known, the human mind cannot process extremely small probabilities very well. As Kahneman and Tversky [1978] noted, highly unlikely events are either ignored or overweighted by most people. Those who ignore unlikely events would be indifferent between a safe job and one with an extra death risk of 0.001 per year. If enough of these individuals were available in the labor market, no additional pay would be required for a risky job. This problem would seem compounded in risky occupations where many of the workers have no formal training in probability theory.

For example, suppose 60 percent of the potential workforce for a relatively risky occupation considers this risk to be negligible, and treats it as though the additional risk were 0.0 rather than a small, positive probability. Then this percentage of the work force would require the same wage rate as that offered in the relatively safe occupation, W_s. The other 40 percent consider this additional risk to be significant, but they have difficulty processing an extremely small probability of, say, 0.001. Kahneman and Tversky [1978] argue that they will therefore act as though this probability is <u>much</u> larger, perhaps by a factor of 10 or more. Given this perception, they would require a much larger wage rate, W_r , to induce them to accept this more risky occupation.

This situation is illustrated in Figure 1. Given our assumptions

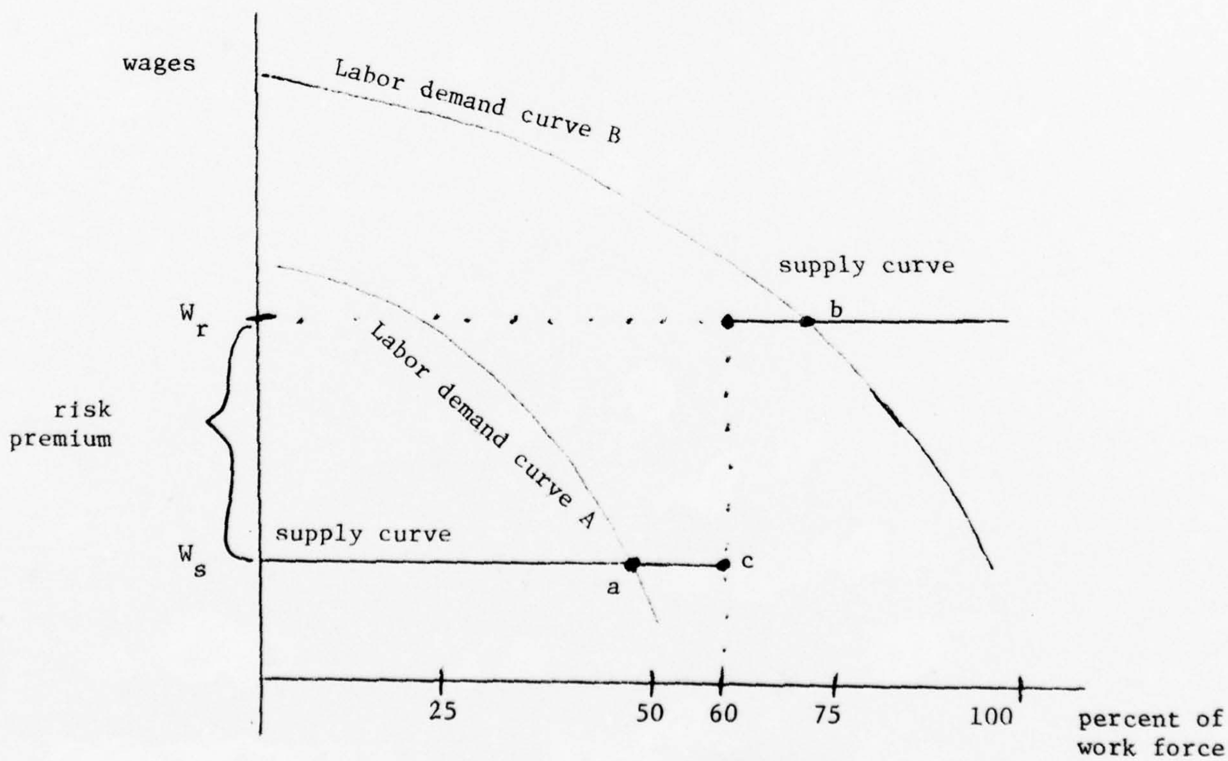


Figure 1. Demand and Supply
Curves for Labor

60 percent of the work force would accept a job in the risky occupation at the same wage rate as the one offered in the safe occupation W_s , but the other 40 percent would require wage W_r. If the labor demand curve intersects the supply curve at point a, as shown for curve A, then no risk premium would be required for the risky job. However, if the demand curve is shifted to the right, as illustrated by B, the point of intersection will be at wage rate W_r , and the risk premium $W_r - W_s$ will be greatly overstated. Notice that essentially the same result is obtained if the supply curve is assumed to be convex to the origin, but discontinuous at point c.

An alternative would be to ask individuals what they would pay (or sacrifice) to reduce a risk. The economists object to this approach since people may respond in their own strategic interest, rather than revealing their true preferences.

Thus, even though the concept of willingness to pay may seem to be an appealing notion, its actual use seems fraught with difficulties.

3.3 The Philosophical Issues

The preceding discussion has identified several of the practical and conceptual difficulties associated with applying cost/benefit analysis to occupational health and safety problems. Criticisms of the approach can be based on even deeper philosophical issues as well.

Ashford [1976] argues that the efficiency criterion cannot be justified in the analysis of policy issues related to human life. This criterion owes its philosophical roots to the ethical theory of utilitarianism, as developed by Mill [1871] and Jeremy Bentham. Utilitarianism states that to judge the rightness of an action we should look to its consequences, and those consequences should provide "the greatest good for the greatest number" (Lee [1977]). According to this principle, it would be ethically acceptable to

adopt an action that causes some individuals to suffer if this is offset by substantial benefits for a larger number of people. This approach is implicit in cost/benefit analysis.

In a recent work, Rawls [1971] has taken exception to this viewpoint. He states that principles of equity and fairness "rule out justifying institutions on the grounds that the hardships of some are offset by the greater good of the aggregate. It may be expedient, but it is not just that some should have less in order that others may prosper." This philosophy seems to be gaining support in our society, where concern for equal opportunity is now being supplemented, if not replaced, by a concern for equal outcomes for all.

As Ashford [1976] notes, "the pursuit of equity may be in conflict with the attainment of other social goals, such as economic efficiency....If so, and if society places a positive value on equity _per se_, it may be sound social policy to forego maximum economic efficiency in order to obtain increased equity." Since cost/benefit analysis ignores the issue of equity, it would not be a useful guide to decision making under these circumstances.

The use of empirically derived "risk premiums" for hazardous jobs is also attacked by Ashford, since it implies an acceptance of the principle of "let the worker beware". He compares this notion to that of _caveat emptor_ (let the buyer beware) in product safety issues, which has been rejected as an equitable principle on the grounds that it imposes an unconscionable contract on the purchaser. In his opinion, hazard pay is not an equitable or socially acceptable substitute for a general improvement in the level of workplace health and safety.

Finally, Ashford [1978] calls attention to the legal mandate of the health oriented regulatory agencies. Specifically, they have been given the

task of ensuring the public against the worst possible outcomes, and not of maximizing expected return. So long as a possibility of risk exists, these agencies must act to prevent it even though the benefits from the action may be great and the probability of harm may be small.

As a recent example of this philosophical dispute within our society, we can witness the break with the Carter Administration by Senator Kennedy over the national health care plan. The Administration plan would link the introduction of the plan to the state of the economy in order to ensure that the new program did not add to the inflationary pressures in the economy. Kennedy argued that good health is a right of the citizens of this country, so these tradeoffs are irrelevant.

Essentially, this debate highlights the main philosophical disagreement over issues of occupational health and safety. Is a safe and healthy working environment an absolute right of a worker, or is it simply one of the "joint products" of the workplace that must be set at an economically efficient level?

A compromise view might be to agree that a safe and healthy working environment is an absolute right of the worker, but that the appropriate level of safety and health must be defined in a careful, reasonable way. One approach would be to design minimum acceptable levels of risk by comparing different occupations, and even by considering the risks associated with leisure activities. This approach avoids either an explicit or implicit attempt to place a monetary value on human life. To implement this approach, we must seek alternate tools of analysis.

4. The Tools of Decision Analysis

The preceding discussion was presented to highlight some of the difficulties encountered in attempts to introduce formal analytical methods into the decision-making process regarding occupational health and safety. Any analytical tool proposed as an alternative to classical cost/benefit analysis must be evaluated in terms of these difficulties.

In this section, we turn attention to three methods of analysis from the field of decision analysis: risk analysis (or risk/benefit analysis), multiattribute utility theory, and social welfare theory. Rather than discuss these methods in the abstract we shall introduce a hypothetical problem, and describe how each of these tools might be applied in the analysis of this problem.

Building Materials Problem. Suppose personnel in the Office of the Chief of Naval Operations are trying to develop a policy regarding the asbestos materials within buildings owned by the U.S. Navy. Their concern is that sprayed-on asbestos exists in the walls and ceilings of some buildings, and, if disturbed, this could be a health hazard for personnel within these buildings. Two programs are currently being considered, and for simplicity we assume that one of them will be chosen:

Program A: PROCEDURES: All existing sprayed-on asbestos materials within Navy-owned buildings will be located and ripped-out immediately. The asbestos will be replaced with alternative materials that produce no health risk.

POLICY: No asbestos will be allowed in any form in Navy-owned buildings.

Program B: PROCEDURES: All existing sprayed-on asbestos materials within Navy-owned buildings will be identified as either crocidolite, chrysolite, or amosite. The crocidolite materials will be ripped out and replaced with alternative materials, since evidence suggests that this type of asbestos is particularly dangerous. The chrysolite and amosite will be inspected and loose or damaged portions will be sealed. A large label will be attached to this material carrying a warning against disturbing the asbestos via demolition or other activities. The location will be noted, and each of these buildings will be inspected annually to ensure that the asbestos is in good repair.

POLICY: Existing chrysolite and amosite asbestos building materials will be inspected and maintained in good condition. No new asbestos materials will be used.

Notice this example requires a choice between two programs. In some cases, an analysis may be performed to accept or reject a program, to choose a subset of programs from among many for implementation, or even to justify a policy that has been chosen previously.

4.1 Risk and Risk/Benefit Analysis

4.1.1 The methodology. Risk analysis describes an attempt to quantify the risk inherent in alternative policies by estimating the probability of death for a specific population group, or by translating this estimate into an expected number of deaths per year. Risk/benefit analysis simply enlarges the task by also assessing the "benefits" associated with an alternative policy. In practice, these "benefits" are net benefits, the sum of all non-risk related benefits minus the sum of all non-risk related costs.

Loosely speaking, risk/benefit analysis may be viewed as a specialized form of cost/benefit analysis. The primary cost is the risk associated with the alternative, so this risk is calculated and emphasized. An important distinction, however, is the omission of an attempt to translate the risk estimate into dollars based on an explicit or implicit market value for human life.

The approach to risk assessment is based on the construction of a probability model. If technical alternatives are being compared, the risk generally arises from the threat of an accident. The risk assessment then involves two phases: 1) an estimate of the number of people who would be killed (or injured) if an accident occurred, and 2) an estimate of the likelihood of that accident. The product of these two numbers is the estimate of risk in terms of expected deaths per year. For example, if a 747 crash would kill an estimated 300 persons, and one crash is expected to occur every 10 years, then the risk associated with 747's is 300 x 1/10 = 30 deaths/year. If there are several different types of accidents that might be associated with an alternative, then one simply uses this same approach for each type, and sums the results.

4.1.2 Examples of applications. The methodology of risk and risk/benefit analysis has gained attention through its use in assessing the risks associated with nuclear power. A massive study on this topic is summarized by Okrent [1977]. This document contains a discussion of the role of risk benefit analysis in society, its relationship to decision analysis, historical perspectives, evidence on societal knowledge of risk, psychological issues, economic issues, risk management, and risk assessment methodologies. It also includes two or three page summaries of more than thirty-five reports completed under this contract, each of which is available.

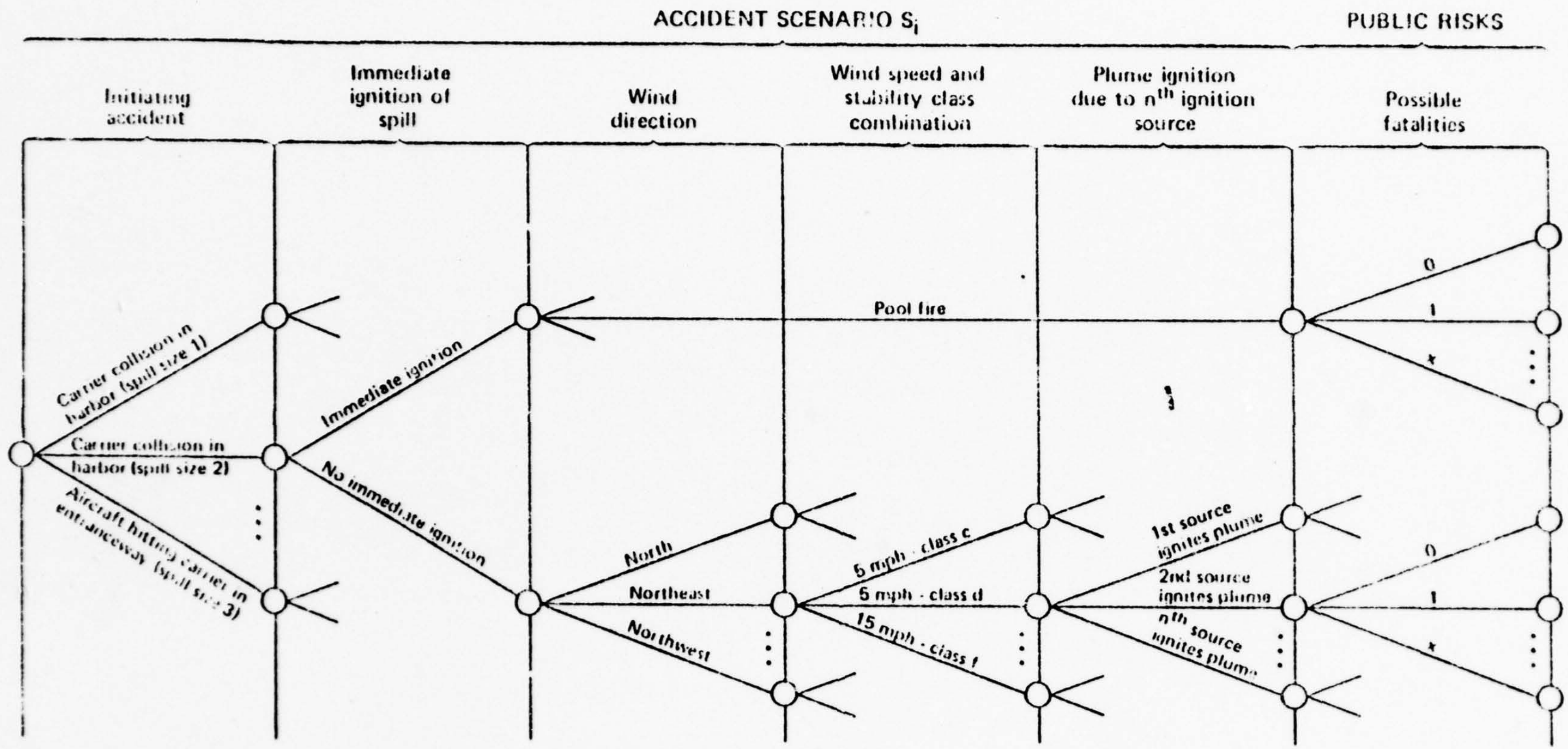
A specific example of a risk analysis is provided by Keeney, Kulkarni, and Nair [1977]. The objective of this analysis was to examine the public risks from accidental releases of LNG due to natural and external man-made events and due to project operations at a marine terminal in Matagorda Bay, Texas. The strategy was to create different accident scenarios, each of which corresponds to a specific sequence of branches in the event tree of Figure 2. For example, one possible scenario would be the following: An LNG carrier collision occurs in the harbor, releasing an LNG spill of a certain size. There is no immediate ignition, so a vapor cloud forms. The wind is from the east at 10 miles per hour with Pasquill stability class D*. The eighth ignition source ignites the vapor cloud. The probability of this or any other scenario would be the product of the following factors:

- Annual probability of the initiative accident,
- Probability of no immediate ignition for that accident,
- Probability of the wind direction,
- Probability of the wind speed and stability class given that wind direction, and
- Probability that the nth ignition source ignites the vapor cloud.

Accident scenarios were constructed for all combinations of the individual events and their probabilities were calculated.

Four categories of public risk were then computed.

- <u>Societal risk</u> - total expected fatalities per year.
- <u>Individual risk</u> - probability of an individual exposed becoming a fatality per year.
- <u>Group risk</u> - probability of an individual in a specific group exposed becoming a fatality per year.
- <u>Risk of multiple fatalities</u> - probability of exceeding specific numbers of fatalities each year.



Note: At each node probabilities are assigned to the various events

Figure 2. SIMPLIFIED EVENT TREE SHOWING EVENTS LEADING TO FATALITIES

source: Keeny, Kulkarni, and Nair [1977].

Although this study focused on risks to the public, similar methods could be applied to estimate the risks to workers from LNG spills.

The final section of the report contains an evaluation of these public risks by comparing them with the public risks associated with existing coal power plants of similar size. The latter estimates can be obtained from historical analysis rather than from modeling. This study determined that the public risk from the LNG terminal was less than one hundred thousandth (1/100,000) of the public risk from a coal plant.

Further evaluation is provided by comparing the risk of an exposed individual to the risk of other unlikely accidents. Examples used were the risk of death from electrocution, being hit by a crashing airplane, a motor vehicle accident, suicide, murder, or being hit by a meteor. The conclusion is that the public risk from the LNG terminal is less than the public risk from any of these other events, except the meteor!

This LNG risk analysis provides an example of a study that could be performed to estimate the occupational risk of an accident from a specific source. A risk analysis based on an occupational disease could be performed in a manner conceptually similar, but it would be much more difficult. The complicating problem is that the key factors in a scenario that lead from the occupational exposure of an individual to a hazardous substance to the occurrence of a disease are not well understood. A few attempts in this important area have been made, however. Bayard [1978] presents a "time to tumor model" for the risk assessment of asbestos induced death from respiratory cancer.

Bayard's model begins by assuming an initiating event (like Keeney, et al.), and estimates the probability of this event causing respiratory cancer and the time lag between the initiating event and the appearance of the tumor. His model is empirically derived from data on amosite asbestos factory workers and insulation workers. The model assumes a linear dose-response relationship between asbestos and cancer, which means that the probability of contacting cancer from an exposure to asbestos is a simple linear relationship. Given that a tumor occurs, the model then assumes a log normal distribution of the time lag. Bayard used his model to estimate the risk for the use of asbestos-containing wall joint compounds. As a matter of interest, his presentation of this approach at the Third FDA Office of Science Symposium was severely criticized by a representative of organized labor because of its many assumptions, and because it implies the existence of an acceptable level of risk.

4.1.3 Application to the building materials problem. To provide a common frame of reference, we now describe how risk analysis or risk/benefit analysis might be applied to the hypothetical building materials problem.

The major issue in analyzing the building materials problem using risk/benefit methodologies would be a comparison of the additional risk associated with Program B against its "benefit" of a relatively lower cost than Program A. For simplicity, we assume that either A or B will be chosen.

The first step would require a cost analysis of both alternatives. Although conceptually simple, this would be a difficult, time-consuming task. Each building containing sprayed-on asbestos would be identified, and cost estimates of its replacement would have to be made. These costs would be increased by the requirement of special handling for the asbestos.

Next, costs associated with Program B would be estimated. The costs of sealing the chrysolite and amosite will be added to the additional cost of an

annual inspection for these buildings. Allowances will also have to be made for occasional repair of the asbestos materials as they deteriorate over time. Nevertheless, the monetary costs associated with Program B should be substantially less than those associated with A.

Again for simplicity, we assume that Program A could be carried out without errors or incidents, so the result would be that the risk from the exposure to asbestos building materials would be reduced to 0.0. To compute the risk associated with Program A, we might proceed in a manner similar to the LNG risk analysis, and identify accident scenarios that lead to exposure. One possibility is illustrated in Figure 3.

In Figure 3, one scenario would be that loose asbestos fibers are accidentally released due to the physical activity of personnel (bouncing tennis balls against the walls, etc.) at a rate equal to an equivalent of exposure to asbestos fibers at a daily dose of 5 fibers/cc. Further, seventy-five persons occupy the building, and the expected asbestos induced cancer-deaths at this exposure level is 0.025. To obtain the risk associated with this scenario, one multiplies the following factors:

- Probability of exposure to fibers due to physical activity
- Probability that physical activity will lead to a 5 fiber/cc daily dose
- Probability that seventy-five persons occupy the building
- The number of persons exposed (75)
- The death rate at 5 fibers/cc (0.025)

Adding the results for each of the alternative scenarios provides an estimate of the total risk. This analysis could be done for each building, but more likely it would be done for categories of buildings of a similar size, construction, and use.

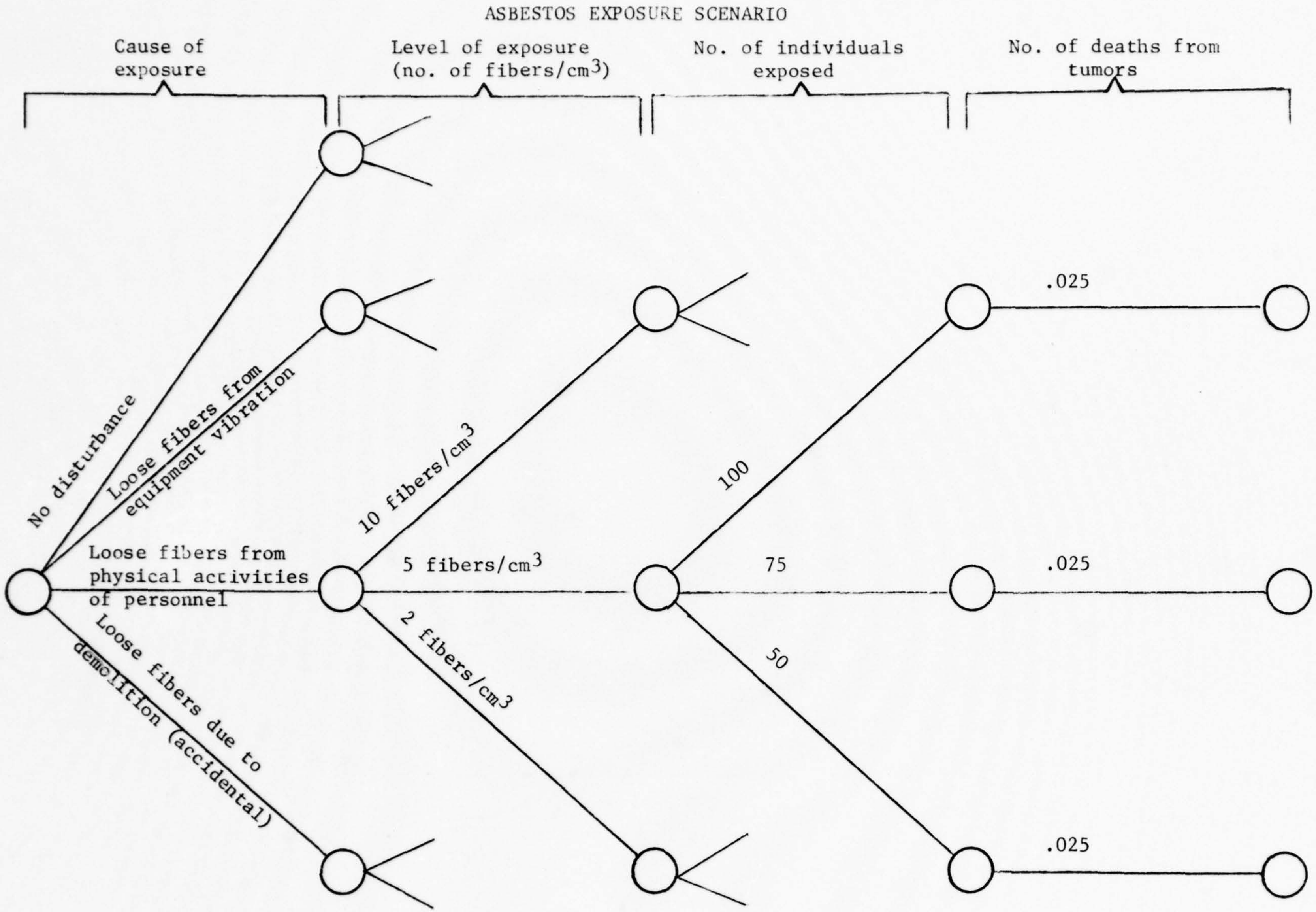


Figure 3. Simplified Event Tree Showing Events Leading to Fatalities

4.1.4 A critique of risk analysis. Like traditional economic analysis, risk analysis or risk/benefit analysis is subject to criticism on both practical and philosophical grounds. From an operational standpoint, the most difficult problem is the estimate of the probability of death or of other serious consequences when the numbers are so small, on the order of 10^{-4} or less.

In the LNG study by Keeney, et al [1977], it was possible to build models to assess the probabilities of different initiating accidents, or of the ignition of a spill by the $n^{\underline{th}}$ source. In the area of occupational health, the physical and biological processes that lead from carcinogenic exposure to a tumor are not well known. In fact, we do not know enough about these processes to be able to positively identify toxic substances as carcinogens prior to the actual observation of an increased cancer rate among humans. Similarly, the effects of loud noises on hearing losses, and of bright lights on eyesight may be difficult to model.

To select one example of an unresolved issue that illustrates this problem, there is considerable controversy over whether or not an "acceptable standard" of exposure for a carcinogen can be determined. Schneiderman [1971] has proposed a methodology for determining the maximum exposure level to a carcinogenic substance for man that is compatible with a socially "acceptable" risk. Essentially, he proposes to experiment with animals subjected to relatively high doses of these carcinogens. These results would then be extrapolated to lower dose levels by assuming a linear dose/response relationship. We then choose an "acceptable" risk level, say 1/100,000 as a lifetime tumor incidence rate, and use the linear dose/response relationship to estimate the "acceptable risk dose" for the species of animal. Schneiderman suggests that this dose

might be reduced by a factor of 100 to allow for the species' differences between man and the test animals, to obtain an "acceptable risk dose" for man, and perhaps reduced even more to allow for other possible errors. Unfortunately, he never indicates how to choose the acceptable risk in the first place!

Rall [1978] discusses in greater detail the problem of extrapolating the results of animal studies to man, and sees some hopeful signs. He points out that twenty-one chemical or industrial processes are known to be associated with the occurrence of cancer in man. Of these, only one substance, arsenic, is not carcinogenic to test animals. However, it may be a co-carcinogen that facilitates the carcinogenic actions of other substances. Further, he cites recent studies that provide evidence that a quantitative relationship exists between the dose/response rate in animals and in man. He also argues for the linear dose/response rate assumption as being a conservative one that seems consistent with known data. Unfortunately, this model does not recognize a "threshold level" of exposure, below which there is no risk. Another complicating factor is that several substances have been shown to be carcinogens in test animals, but there is no evidence that they cause cancer in man.

Robock [1978] argues that this concept of an "acceptable" risk level can be applied to the problem of industrial exposure to asbestos by identifying the "threshold level" of exposure, below which the risk of asbestos induced tumors is essentially zero. Data involving tumor rates among asbestos workers (rather than animals), indicates a dose-response relationship and perhaps a "threshold" level as well. Robock interprets his figures as indicating that exposure to asbestos at 2 fibers/cc or less involves no risk to humans.

Englund [1978] takes issue with Robock, and says that we cannot be <u>sure</u> there is a safe level of exposure to asbestos. He also argues that there are many alternative substances that perform the same function as asbestos, so they should be used instead of asbestos to avoid the asbestos risk entirely.

To summarize this discussion, risk/benefit analysis is criticized because the estimates of the probability of death are not known. At first glance, this may seem no different from a classical capital investment decision where the returns are not known with certainty, and yet a decision must be made. To proceed, one simply estimates the subjective probability of several levels of the monetary outcome, and computes the expected value of the outcome. However, in a risk/benefit analysis, the outcome of interest is the <u>risk</u> itself. There is no general agreement on the model that relates exposure to a tumor rate, even though several alternative models have been proposed. To apply the classical decision theoretic approach, we would have to estimate the probability that each of these <u>alternative</u> dose/response models is correct, and compute an expected value for the alternative models. Note that such an approach would be subject to criticism by Ashford and others, who argue that workers must be protected against the <u>worst possible</u> outcome in terms of risk, rather than against some "expected" risk based on conflicting judgments.

Another difficulty with risk and risk/benefit analysis is the recognition that equal risks associated with different activities may be evaluated very differently by society. For example, society may tolerate the activity of skiing with relatively high risk, and object to the establishment of nuclear power plants with a relatively low risk, where risk is defined as the probability of death per 100,000 persons exposed. In a classic paper, Starr [1969] identified the concepts of voluntary risk versus involuntary risk as influencing the public's attitude toward an "acceptable" level of risk. More recently, other dimensions of risk have been identified which may affect its perception by society. Lowrence [1976] suggests the following nine dimensions:

1. Voluntariness of risk: Do people get into risky situations voluntarily?
2. Immediacy of effect: To what extent is the risk of death immediate -- or is death likely to occur at some later time?
3. Knowledge about risk: To what extent are the risks known precisely by the persons exposed to them?
4. Knowledge about risk: To what extent are the risks known precisely by science?
5. Control over risk: To what extent can the exposed individual avoid the risky consequence by virtue of his skill?
6. Newness: Are the risks new or old?
7. Chronic-catastrophic: Does the risk kill people one-at-a-time or in groups?
8. Common-dread: Do people have a great dread of the consequence?
9. Severity of consequence: If a mishap occurs, how likely is it to be fatal?

Using these dimensions, Fishhoff, Slovic, Lichtenstein, Read, and Combs [1977] found that greater risk was tolerated if it was voluntary, immediate, known precisely, controllable, and familiar.

Rowe [1977] has suggested that we develop risk conversion factors to make all risks equivalent in terms of their social perception. For example, he suggests that a risk involving N persons simultaneously is perceived as being N^2 times as important as an accident involving one person. Thus, an airplane crash killing 100 persons is perceived as $100^2 = 10,000$ times as serious as an automobile killing one person. He has performed an elaborate study of fatality data, and has developed risk conversion factors for accidents occuring

in poor countries versus rich countries, natural catastrophes versus man-triggered catastrophes, statistical risk versus identifiable risk, and so on. Although his approach has some intuitive appeal, it seems to lack a firm theoretical foundation. The notion of evaluating risk as a multiattributed phenomenon seems to be worthy of further research, however.

Finally, a risk/benefit analysis avoids the issue of equity, much like classical cost/benefit analysis does. That is, the risks may be borne by one segment of the population while the benefits accrue to others. Highland [1978] argues that "... the only truly 'acceptable' risk is one incurred by deliberate choice, in preference to feasible alternatives, by those individuals who stand to suffer harm from the risks involved." Elaborating on this point, he states the following:

> How should society analyze and evaluate the risks and benefits? For example, do the benefits from the production of polyvinyl chloride for the fabrication of plastic novelty items outweigh the cancer risks inherent in such production? Are the carcinogenic risks to those occupationally employed or those in the immediate vincinity of the plant exposed to vinyl chloride air emissions outweighed by the "benefits" of enjoyment that will be derived from such articles? Can such involuntary risks be justifiably compared to other risks in society which involve personal choice and therefore, a direct personal trade-off between risks and benefits? Or must we realize that, rather than trying to justify such risks as "minimal" or comparable to others, we have an obligation to eliminate as quickly as possible such risks where they currently exist and to prevent further ones from developing in the future. The simply stated question is: under what conditions, if <u>any</u>, is someone in society entitled to impose a risk on someone else for the sake of a supposed benefit to yet others (Highland [1978])?

It seems unlikely that this last question has an answer that will meet with unanimous acceptance in our society.

We seem to be left with the conclusion that risk analysis and risk/benefit analysis are useful methods for supplying information for decisions in the area of occupational health and safety. However, the results of these studies

will not be used for decision making without careful consideration of other issues. As we have noted, these studies are limited in the following ways:

- No agreement on the appropriate probability models for estimating the risk associated with exposure to carcinogens and other occupational hazards
- No agreement on the notion of an "acceptable risk"
- No agreement on the issue of how risks differ, and how to interpret factors like voluntary versus involuntary risk
- No agreement on how to deal with the issues of equity.

Thus, there will still be many questions left unanswered by a risk or risk/benefit analysis.

4.2 Utility Theory

4.2.1 The methodology. Utility theory is used to quantify value judgments regarding the relative desirability of the consequences associated with alternatives. If these consequences involve multiple dimensions, then a multiattribute utility function can be used to aggregate the values associated with the different dimensions. For example, a risk/benefit analysis would calculate the risk and the non-risk benefits associated with different alternatives. A multiattribute utility function could be used to assign subjective values to the levels of risk and benefits, and to aggregate these subjective values into a single number.

The development of a multiattribute utility function that assigns values to multi-dimensional consequences assumes there is either a single decision maker, or a group of people that can be expected to reach a consensus on their value judgments.

Essentially, the utility function is merely an explicit representation of the preferences of the decision maker. Through a dialogue with the decision maker, the analyst elicits enough information so that he can determine the form of the utility function.

In the area of occupational health and safety, this approach avoids the problem of trying to estimate an implied market value for human life. However, it may require the decision maker to reveal his own subjective judgment regarding the value of a human life, which may or may not be related to any notion of its market value. Since any such statement would be extremely controversial, it seems that public officials would be reluctant to provide these responses. As we shall see, this problem may severely limit the number of actual applications of multiattribute utility theory to occupational safety and health problems.

4.2.2 Examples of applications. We were unable to discover any actual applications of multiattribute utility theory to the evaluation of projects involving public risk. This may be due to the problem of identifying a single decision maker in this context and making explicit his preferences. We did, however, find two examples of the parametric analysis of hypothetical utility functions for problems similar to those in occupational safety and health. In each case, the analyst hypothesized the appropriate criteria for the decision maker and argued for a specific parameterized functional form. Then they investigated the sensitivity of decisions to variations in the parameters of the utility functions. If one could conclude that a specific policy is most desirable for a wide range of parameter values, then it follows that this policy should be selected without requiring the decision maker to be more specific about his parameter values so long as they fall within this range.

The first study was performed by Maurer [1977] in the context of a comparison

of coal and nuclear electricity generation. To simplify his analysis, Maurer assumed the only criteria of interest were monetary costs and increases in mortality. For both practical and theoretical reasons he argued that the most appropriate utility function would be of the form

$$u(x,y) = c_x u_x(x) + c_y u_y(y)$$

where x is the monetary cost, y is the increase in fatalities, and c_x and c_y are relative weights of importance.* He also suggests that

$$u_x(x) = -\exp(-x/a_x)$$

and

$$u_y(y) = -\exp(-y/a_y)$$

are reasonable forms for u_x and u_y, respectively.

Empirical studies have shown that most individuals are averse to monetary risk; that is, they would prefer the expected monetary value of a risky alternative to accepting the risky outcome when it is realized. This implies that $a_x \geq 0$. For this study, the values of $a_x = +\infty$, 200, 100, 66.6, 50, and 40 were used to explore a wide range of possible risk averse preference structures.

The choice of a_y is a bit more difficult to rationalize. Some experts argue that u_y should also be risk averse, since a catastrophe that kills 100 people is considered almost as "bad" as one that kills 200 people. Others would argue that each human life should be valued equally, so that a_y should equal ∞ (as $a_y \to \infty$, $-\exp(-y/a_y) \to y$). Therefore, values of $a_y = \infty$, 200, 100, 66.6, 50, and 40 were used.

Finally, the ratio of c_x to c_y must be selected, and this ratio reflects

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* Both $x \leq 0$ and $y \leq 0$, since they represent losses.

the tradeoff ratio between increased fatalities and costs. Since the value of life is the marginal rate of substitution of monetary losses for increased mortality, holding utility constant,

$$\text{value of life} = (\partial u(x,y)/\partial y)/(\partial u(x,y)/\partial x)$$

so we obtain

$$c_y/c_x = (\text{value of life})(u_x'(x))/(u_y'(y))$$

where u_x' (u_y') is the derivative of u_x (u_y) evaluated at $x = 0$ $(y = 0)$. Values of life of \$250,000, \$500,000, and \$1,000,000 were used in the study, and transformed into c_x and c_y values through this relationship.

Finally, actual data and estimates were obtained for coal and nuclear plants, respectively. The parametric analysis revealed that the choice between the two technologies was most sensitive to the parameter a_y that determines the risk aversion of the decision maker with regard to fatalities. If $a_y \geq 200$, the nuclear facility is always preferred, while if $a_y \leq 66.6$, the coal facility is always preferred. Only when a_y is between these values does the choice of the most desired alternative depend on the values of a_x, c_y, and c_x.

The second study was by Keeney [1978b], and followed a similar, but more complex line of reasoning. In our discussion of risk analysis, we noted that all risks involving an equal probability of death are not viewed as equal by society. For example, a higher risk is more likely to be "acceptable" if it is taken voluntarily by an individual. Keeney presents a detailed rationale for the general form of utility function

$$u(x,y) = -x - \lambda y + \beta\{\frac{1}{h}[(1-h)^x - 1] + \frac{\mu}{d}[(1-d)^y - 1][(1-h)^x]\}$$

where x = the number of fatalities due to involuntary risks,

y = the number of fatalities due to voluntary risks,

h = weight given to the societal impact of one fatality due to involuntary risks relative to the societal impact of N fatalities due to involuntary risks,

d = weight given to the societal impact of one fatality due to voluntary risks relative to the societal impact of M fatalities due to voluntary risks,

λ = weight given to the personal impact of a fatality due to voluntary risks relative to the personal impact of a fatality due to involuntary risks,

μ = weight given to the societal impact of the first fatality due to voluntary risks relative to the societal impact of the first fatality due to involuntary risks,

β = weight given to the societal impact of the first fatality due to involuntary risks relative to the personal impact of that fatality.

Keeney acknowledges that the assessment of these parameters would be a difficult task, but offers some suggestions regarding how this might be done.

4.2.3 Application to the building materials problem. An application of multiattribute utility theory to the building materials problem might take a form similar to the study by Maurer [1977]. The first step would be to identify the decision maker or the decision-making group. Then, the analyst would work with the decision maker to identify the appropriate criteria for the analysis. Suppose the criteria are determined to be the following:

- cost in dollars, x
- risk in expected fatalities, y
- image measured on a subjective scale, z.

The latter factor, image, is included because the decision maker might prefer a more costly alternative to one with an equal risk level if it would clearly demonstrate to the employees and to the public that the organization is deeply concerned about occupational safety and health.

The two alternative programs for solving the building materials problem would then be analyzed to determine their outcomes in terms of these three criteria. If there is risk associated with these outcomes the probability of each must also be estimated.

Policy A which requires a complete rip-out would be relatively costly. As a rough estimate, suppose there are 200 buildings to be renovated at a mean cost of $200,000 each. The total cost of this option would be $40 million. Policy B would require only the sealing of the asbestos. If this could be done for only $30,000 per building, the total costs would be $6 million.

Policy A would be completely "safe" with regard to asbestos related deaths. However, there is some slight risk associated with Policy B since some of the asbestos could be disturbed, and there is some positive probability that the subsequent exposure of personnel could cause tumors among some individuals. Suppose we obtain the probability estimates shown in Table 1 for the various numbers of deaths shown. The analysis required to obtain these estimates would be identical to the approach followed to estimate the "risks" in a risk analysis.

Finally, suppose we use the adjectives "good," "neutral," and "bad" to

Number of Deaths		
Range	Mid-Range Value	Probability
0	0	0.8
1 - 5	3	0.1
6 - 24	15	0.08
25 - 45	35	0.01
46 - 154	100	0.009
155 - 295	225	0.0005
296 - ∞	400	0.0005
		1.0000

Table 1. Probabilities of Alternative Levels of Fatalities

describe the impact on the image of the Navy associated with the adoption of these programs. Unfortunately, we are not sure what the public reaction would be. Suppose we estimate that Policy A would be perceived as having a "good" impact with probability 0.5, and a "neutral" impact with probability 0.2. However, there is a 0.3 chance that the impact will be "bad" because it will be seen as wasteful, and as an admission that personnel have previously been kept in a dangerous environment.

Policy B is even more difficult to assess in this regard. If there are no deaths eventually attributed to the policy, there is a 0.2 probability that this action will have a "good" impact on image, a 0.5 probability that it will have a "neutral" impact, and only a 0.1 chance of a "bad" impact. However, if deaths actually occur, the probability of a "bad" impact would rise sharply. Thus, the attributes "deaths" and "image" would <u>not</u> be indepen-

dent in terms of their joint probability of occurrence. The assessment of joint probabilities is a difficult task, as noted by Sarin [1978a, 1978b], who provides some methodologies that might be adopted for this task. Suppose we obtain the outcome estimates shown in Table 2.

	Cost*(x)	Deaths(y)	Image**(z)	Probability(p)
Policy A	40	0	g	0.5
	40	0	n	0.2
	40	0	b	0.3
Policy B	6	0	g	0.2
	6	0	n	0.5
	6	0	b	0.1
	6	3	g	0.005
	6	3	n	0.05
	6	3	b	0.045
	6	15	g	0.005
	6	15	n	0.025
	6	15	b	0.05
	6	35	g	0.001
	6	35	n	0.002
	6	35	b	0.007
	6	100	g	0.0
	6	100	n	0.001
	6	100	b	0.008
	6	225	g	0.0
	6	225	n	0.00005
	6	225	b	0.00045
	6	400	g	0.0
	6	400	n	0.0
	6	400	b	0.0005

Table 2. Probabilities of Outcomes

*cost in millions of dollars

**g = "good," n = "neutral," and b = "bad"

The next task would be to assess the decision maker's multiattribute utility function over these three criteria. A series of questions would be asked to determine whether these criteria are independent in some sense, so that the utility function could be decomposed. Suppose the decision maker is indifferent among all even chance lotteries in which each criterion has identical marginal probability distributions. For example, he would be indifferent between an even chance lottery with ($40 million, 100 deaths, good) and ($6 million, 0 deaths, bad) as outcomes, and an even chance lottery with ($40 million, 0 deaths, good) and ($6 million, 100 deaths, bad). Note that the outcomes of these two lotteries differ in the way that the values are combined, but there is an equal chance of a cost of $40 million or $6 million, an equal chance of 0 deaths or 100, and an equal chance of a good impact or a bad one. If his preferences satisfy this condition, then Fishburn [1970] has shown that

$$u(x,y,z) = \lambda_x u_x(x) + \lambda_y u_y(y) + \lambda_z u_z(z)$$

where λ_x, λ_y, and λ_z are scaling constants (see also Keeney and Raiffa [1976, Chapter 5]). If the decision maker were not indifferent among these even chance lotteries with identical marginal probability distributions, then a more complex form of the utility function would be required. The analysis would proceed in essentially the same way, however.

The assessment of u_x is trivial, since there are only two values of cost to be considered. We let $u_x(40) = 0$ and $u_x(6) = 1.0$ to reflect the fact that a cost of $6 million is preferred to one of $40 million.

To assess u_y, suppose we assume that the decision maker values all lives equally. Therefore, u_y is linear in y. For convenience, we set $u_y(0) = 1$ and $u_y(400) = 0$. For any $y \in [0,400]$, we define

$$u_y(y) = (400 - y)/400$$

so that $u_y(100) = (400 - 100)/400 = 0.75$, for example.

Since there are only three possible criterion values for image, we can let $u_z(\text{bad}) = 0$ and $u_z(\text{good}) = 1.0$. To determine $u_z(\text{neutral})$, we ask the decision maker to identify a probability p so that he would be indifferent between accepting a policy with a neutral impact on image for sure, or risky one that would have a p chance of a "good" impact, but a $(1 - p)$ chance of a "bad" impact. Suppose he says $p = 0.75$. Then $u_z(\text{neutral}) = 0.75$.

Finally, we must assess the scaling constants λ_x, λ_y, and λ_z. Notice that the relationship between λ_x and λ_y reveals the decision maker's estimate of the value of a life saved from the risks associated with this project. As we have noticed, different risks may be viewed differently, so there is no reason to assume that this same value would be used to evaluate all risky projects. Suppose the decision maker were indifferent between the following outcomes: ($40 million, 0 deaths, bad) and ($6 million, 170 deaths, bad). This implies that each life "saved" would be worth ($40,000,000 - $6,000,000)/170 = $200,000 to the decision maker. This decision regarding the appropriate tradeoff between dollars and lives would be an explicit value judgment that may or may not be influenced by the estimates of a value of a life by economists.

Given this statement of indifference, we have

$$\lambda_x u_x(40) + \lambda_y u_y(0) + \lambda_z u_z(\text{bad}) = \lambda_x u_x(6) + \lambda_y u_y(170) + \lambda_z u_z(\text{bad})$$

and, substituting for the functions u_x, u_y, and u_z, we have

$$\lambda_x \cdot 0 + \lambda_y \cdot 1 + \lambda_z \cdot 0 = \lambda_x \cdot 1 + \lambda_y \cdot 0.575 + \lambda_z \cdot 0$$

which simplfies to $\lambda_y = 2.353\ \lambda_x$.

Similarly, suppose the decision maker is indifferent between ($40 million,

3 deaths, neutral) and ($6 million, 3 deaths, bad). Then $\lambda_z = 1.333\lambda_x$. By requiring $\lambda_x + \lambda_y + \lambda_z = 1.0$, we can now solve for the scaling constants, and obtain the utility function

$$u(x,y,z) = 0.22u_x(x) + 0.5u_y(y) + 0.28u_z(z).$$

We now compute the expected utility associated with each alternative by using $u(x,y,z)$ to calculate the utility function value associated with each outcome, multiplying each outcome by the probability of its occurrence, and summing the results. The calculations for Plan A are shown in Table 3. The

x	y	z	u(x,y,z)		p	p·u(x,y,z)
40	0	g	(0.22)(0) + (0.5)(1) + (0.28)(1)	= 0.78	0.5	0.39
40	0	n	(0.22)(0) + (0.5)(1) + (0.28)(0.75)	= 0.71	0.2	0.142
40	0	b	(0.22)(0) + (0.5)(1) + (0.28)(0)	= 0.5	0.3	0.15
						0.682

Table 3. Expected Utility Calculations for Policy A

expected utility of Plan A is found to be 0.682. In a similar manner, the expected utility of Plan B was determined to be 0.905, making it clearly superior to Plan A.

At this point, a sensitivity analysis would be carried out to determine whether small changes in the estimates of the scaling constants λ_x, λ_y, and λ_z or in the probabilities would reverse these ratings. In this hypothetical example, it is clear that small changes would not reverse these rankings. Either the ratio of λ_x to λ_y would have to change <u>drastically</u> to alter the choice, or the ratio of λ_x to λ_z would have to change <u>drastically</u>. Otherwise, the small probabilities associated with the adverse consequences of Plan B will continue to favor it over Plan A.

4.2.4 A critique of utility theory. Utility theory is used to elicit the subjective values of a single decision maker. There is no pretense of "scientific objectivity" as seen in economic cost/benefit analysis. This creates a conceptual problem, since we like to think that decisions made on an objective basis will be accepted by everyone. Once we admit that the basis for the decision is subjective, we also recognize that someone with different values may legitimately reach a different conclusion. Thus, the obvious question is the following: Whose values should be used to make decisions regarding occupational health and safety?

From a practical standpoint, many decision makers might hesitate to have their values made explicit as required by this methodology. Further, there may be personal criteria, such as the impact of a decision on the decision maker's career, that he may wish to consider, but not to make public. These considerations may help to explain why multiattribute utility theory has not been applied more widely in the public sector.

Keeney and Raiffa [1976, Chapter 1] recognize that these problems exist, and yet decisions must be made. They argue that these complications make the application of multiattribute utility theory much more difficult, but it still can be used in many cases.

Fischhoff, Slovick, and Lichtenstein [1978] raise deeper questions about multiattribute utility theory. They note that the values of a decision maker do not actually exist firmly in the decision maker's mind. Rather they may be formed and molded during the assessment procedure that seeks to elicit them. Further, different assessment procedures may affect these values differently, and actually change the preferences of the subject.

> Expressed values seem to be highly labile. Subtle changes in elicitation mode can have marked effects on what people express as their preferences. Some of these effects are reversible, other not; some deepen the respondent's perspective, other do not; some are induced deliberately, other not; some are specific to questions of value, other affect judgments of all kinds; some are well documented, others are mere speculation (Fischhoff, Slovic, and Lichtenstein [1978]).

In summary, it seems clear that utility theory is a tool with potential use as an aid in decisions regarding occupational health and safety, but this use will generally be limited. Situations that would be candidates for the use of this approach would include an easily identifiable decision maker or decision making group. In addition, these decisions would probably be operational where there are a limited number of involved interest groups, rather than strategic or policy decisions that are subject to a great deal of public attention and debate.

4.3 Social Welfare Theory

4.3.1 The methodology. Suppose the agency or the organization concerned with occupational safety and health adopts the following viewpoint: The appropriate criterion for decisions in this area is not the preferences of some single decision maker; rather, the criterion must synthesize the preferences of those individuals who will be affected by the decisions. The objective of the agency, therefore, is to determine a rule that synthesizes these diverse expressions of preference. This rule must be based on some notion of "fairness" or of "equity," but these important concepts have no unique definition in our society. Thus, a rule consistent with one concept of fairness may be at odds with another one. It seems unlikely that a single rule for the synthesis of preferences will be simultaneously consistent with the diverse ideas of justice, but these rules may still help to choose among alternatives.

Social welfare theories may be based on either ordinal or cardinal expressions of preference by the individuals involved. Ordinal expressions of preference simply allow a statement that A is preferred or indifferent to B, but no expression of "strength of preference" is considered. That is, there is no attempt to measure by "how much" an individual prefers alternative A to alternative B. This creates some difficulties for any theory of social choice, but these difficulties are exaggerated in the context of occupational safety and health.

For example, suppose we have a simple problem where only two individuals, a worker and an employer, are involved in choosing between alternatives A and B. The worker prefers A to B because he is much less likely to be killed if A is selected. The employer prefers B to A because it will save him $10 per year. Most theories of social choice based on ordinal expressions of preference would not distinguish between alternatives A and B under these circumstances. Yet, most observers would argue that the worker <u>strongly</u> prefers A to B, while the employer only has a slight preference for B over A, so A should be selected.

Because of this limitation of social welfare theories based on ordinal preferences, we shall focus here on theories based on cardinal expressions of preference. These cardinal preference representation functions may be based on either von Neumann and Morgenstern utility theory (e.g., see Harsanyi [1977], Keeney and Raiffa, Chapter 10 [1976]) or on measurable value functions (e.g., see Dyer and Sarin [1978a,1978b]).

Suppose the decision maker feels that the decisions made by (or for) the affected individuals should be consistent with the von Neumann and Morgenstern [1944] rationality axioms. Further he adopts the following rule as a notion of

"equity": If all individuals are indifferent between two alternatives defined by probability distributions over the consequences, then the group will be indifferent between them. Then the appropriate social choice function is given by

$$W(x) = \sum_{i=1}^{n} k_i u_i(x)$$

where u_i is individual i's utility function, k_i is a "scaling constant," and x is the consequence associated with an alternative.

Alternative rules of equity will lead to other forms of the social welfare function, as discussed by Keeney and Kirkwood [1975]. However, we shall restrict our discussion to this simple additive form, since most of the following comments would be relevant for the alternative forms as well.

The use of the social welfare function requires two steps. First, the utility functions u_i, $i = 1, \ldots, n$, must be assessed. Next, the scaling constants k_i, $i = 1, \ldots, n$, must be assigned. Loosely speaking, these constants reflect the relative importance of the preferences of each individual. As we shall discuss later, neither of these steps may be easy to operationalize, since they require explicit interpersonal utility comparisons.

As a brief digression, it is interesting to view cost/benefit analysis as a special case of the more general social welfare function. Specifically, suppose we let

$$k_i u_i(x) = \sum_{j=1}^{m} b_{ij}(x) - \sum_{\ell=1}^{s} c_{i\ell}(x)$$

where b_{ij} = the market dollar equivalent of the added amount of benefit j accrued to individual i if policy x is chosen, and

$c_{i\ell}$ = the market dollar equivalent of the additional amount of cost ℓ accrued to individual i if policy x is chosen.

Thus, benefit/cost analysis and the additive social welfare function will lead to the same results _if_ we can impute a market value for all benefits and costs, _if_ we assume that each individual i values benefits and costs at their market values, and _if_ we assume that the value of each additional dollar is constant and equal among all individuals. As we noted in our earlier critique of cost/benefit analysis, these assumptions are the basis for considerable concern in the context of occupational safety and health decision making.

4.3.2 _Examples of applications_. The only real-world application of social welfare theory of which we are aware is the trajectory selection study by Dyer and Miles [1976, 1977]. Although this study seems far removed from the topic of occupational safety and health, a brief summary may be useful.

Trajectories were required for the two Voyager space craft launched in 1977 for Jupiter and Saturn. The space craft are identical and carry instruments that provide information to ten science teams. Unfortunately, each science team preferred a different trajectory pair in order to maximize the quantity and quality of the information that they will receive.

The Project Manager at the Jet Propulsion Laboratory felt that the final decision regarding these trajectories should be based on the preferences of the science teams. Thus the trajectory selection problem was viewed as a 10-person social welfare maximization problem, with the teams corresponding to persons.

Dyer and Miles used the additive social welfare function for this study. To operationalize this approach, they were required to consider the related issues of interteam normalization through the scaling of each science team's utility function and the choice of the k_i's, the weighting factors.

Suppose for each science team i, we identify t_i^* and t_{i*}, their best and worst feasible trajectory pair, respectively. We arbitrarily scale each u_i so that $u_i(t_i^*) = 1.0$ and $u_i(t_{i*}) = 0.0$. Ideally, we would like the "utility differences" between $u_i = 1.0$ and $u_i = 0.0$ to be the same for each team. Dyer and Miles attempted to accomplish this by ensuring that the trajectory pairs t_i^* and t_{i*}, respectively, determine similar consequences for each team.

A "no data" trajectory pair was introduced into the set of alternatives, and identified as an alternative that gave no useful information because of equipment malfunction. It was assumed that $u_i = 0$ for this no data pair for all teams, and that all teams would feel "equally bad" about that result. Note that the "no data" pair might be viewed in a similar way as the outcome of "death" in an occupational safety and health problem.

The teams were allowed to participate in generating alternatives, and to ensure that their <u>best</u> trajectory pair was also among the alternatives. Thus, Dyer and Miles assumed that the magnitude of the preference difference between t_i^* and t_{i*} was essentially the same for each team i.

The next problem was the choice of the weighting factors, the k_i's. The Project Manager was extremely reluctant to assign weights that would imply that one science team experiment was more important than another, so equal weights were used. However, the information provided by some experiments was <u>clearly</u> more sensitive to the choice of the trajectories than for others. As a "sensitivity analysis," these teams were given a higher weight and the analysis was repeated. There were no significant differences in the results.

Each science team provided a ranking and cardinal utility function values for a set of thirty-two candidate trajectory pairs. The trajectory pairs were

evaluated using the additive social welfare function. Some sensitivity analysis was performed on the scaling of the utility functions and on the weighting factors. The results were presented to the scientists and actually used in their deliberations leading to the choice of the trajectory pair.

A hypothetical study of considerable interest was done by von Winterfeldt [1978] on the standard setting process for chronic oil discharges in the North Sea. We are naturally interested in this question because of the obvious analogy to the problem of determining standards for the exposure of workers to potentially harmful substances.

von Winterfeldt began by identifying the three main decision making units that are involved in the regulatory process (see Fischer and von Winterfeldt [1978]):

- The regulator -- the people and institutions that set an environmental standard, monitor its compliance, and sanction its violations
- The developer -- typically industrial groups whose actions are restricted by the regulations
- The impactees -- groups impacted by the pollution generated by the developer.

He then developed a hypothetical utility function for <u>each</u> of these units based on logical arguments much like Maurer's approach. The novelty in this approach is the construction of the functions for each interested party rather than an attempt to model the preferences of <u>the</u> decision maker.

For the regulator, he suggested the utility function

$$u_r(s\ell) = \sum_{i=1}^{4} w_{ri} v_{ri}(s\ell)$$

where $s\ell$ is the standard level for pollution, and

$$v_{r1}(s\ell) = 100\ e^{-\frac{(s\ell-30)^2}{145}}$$

values how well the standard level agrees with those set by other nations,

$$v_{r2}(s\ell) = 100\ e^{-.014s\ell}$$

values how well the standard satisfies international demands for a clean North Sea,

$$v_{r3}(s\ell) = 100 - 100\ e^{-.014s\ell}$$

values the influence of the standard on the national policy of rapid oil development in the North Sea, and

$$v_{r4}(s\ell) = 100\ e^{-\frac{(s\ell-40)^2}{577}}$$

values how close the standard level is to the "best practical" level of pollution with the current technology, and the w_{ri}, $i = 1, 2, 3, 4$, are weighting factors.

The utility function for the developer is a bit more complex. There are seven alternative technologies, $d_1, \ldots, d_7$, for reducing chronic oil spills, ranking in order from 1 to 7 of increasing cost and increasing effectiveness. For a specific standard level $(s\ell)$ and inspection procedure (sm),

$$\begin{aligned} u_d(d_j) = & -p(\text{violation detection})(c_d(d_{j+1}) + K_0) \\ & - (1 - p(\text{violation detection}))c_d(d_j) \end{aligned}$$

where $c_d(d_j)$ is the cost of technology d_j and K_0 is the fine associated

with being detected in violation of the standard. The model assumes that the developer will be required to replace technology d_j with the "next best" technology if a violation is detected. This model assumes a risk neutral attitude towards costs, but von Winterfeldt also suggests a risk averse version of this model as an alternative.

By assuming costs for the technologies, costs for the violation penalties, different standards and monitoring systems, and different probability distributions regarding the actual <u>effectiveness</u> of each technology, von Winterfeldt carried out an extensive parametric evaluation of the developer's best response. "Cut-off" probabilities of violation detection were identified for each technology.

Finally, the impactee model was simplified to

$$u_i = -\ell$$

where ℓ is the actual emission level. This was used as a surrogate for the impact of ℓ on fish populations and other ecological disturbances due to the difficulty of measuring them.

To complete the analysis, von Winterfeldt investigated all three utility functions simultaneously to rule out alternative regulatory standards that were <u>dominated</u> over a wide range of parameter values. This analysis was quite thorough, and indicated that the best standards were near the cutoff points that just barely allowed the developer to use the "next cheaper" technology and yet provided the highest standard within the effective range of that technology. Further analysis suggested that a standard somewhere between 30 and 40 parts per million would be "good" when the utility functions of all three groups were simultaneously considered.

To complete the link with social welfare theory, von Winterfeldt suggests that these three functions might be used in the additive form

$$u = \lambda_r u_r + \lambda_d u_d + \lambda_i u_i$$

to identify the Pareto optimal set of regulations (those regulations where no other regulation is preferred by every one of the three interest groups). This form, of course, corresponds to the additive social welfare function.

4.3.3 Application to the building materials problem. An application of social welfare theory to the building materials problem might look very similar to the application of multi-attribute utility theory. This is because the attributes selected for the previous study were considered to be important as a result of their impacts on various interest groups.

To illustrate this notion, suppose we identify the relevant interest groups in this problem as follows:

- .the Navy as an organizational entity
- .employees and enlisted men potentially exposed to risk
- .taxpayers.

This choice corresponds loosely to the categories of employers, employees, and consumers that we identified in the discussion of actors in Section 2.2.

In order to implement social welfare theory, we need to determine utility functions for each of these three interest groups. In most applications, it would not be practical to identify a spokesman for each group, and actually assess his utility function. Harsanyi [1977] suggests that the decision maker should use "imaginative empathy" instead, and imagine himself in each affected individual's shoes. He should be able to recognize the criteria that would be important to each individual or interest group, and to hypothesize a utility function that would reflect the values of each group reasonably well. If necessary, the results could be subjected to a

sensitivity analysis to evaluate changes in these functions. This is essentially the approach used by von Winterfeldt [1978].

In Section 4.2.3, we created an illustrative utility function for a decision maker representing the best interests of the Navy, and obtained the following:

$$u_n(x,y,z) = 0.22u_{nx}(x) + 0.5u_{ny}(y) + 0.28u_{nz}(z)$$

where u_{nx}, u_{ny}, and u_{nz} are conditional utility functions on the attributes x=costs, y=fatalities, and z=image, respectively. The use of the additional subscript n denotes that this is the Navy's utility function. Here we shall use this function again to represent the Navy's preferences.

The employees and enlisted men are assumed to be concerned only with the risks involved in this problem area. Therefore, we can let $u_{ey}(y)$ be the utility function for the employees (e). It seems reasonable to assume that each additional life would be valued equally by this group, so $u_{ey}(y)$ would be identical in form to $u_{ny}(y)$ (see Keeney [1978] for a justification of this idea).

Finally, the taxpayers will be concerned about the costs, and may also provide a "societal conscience." That is, they will be concerned about fatalities that result from policy decisions rather than from natural causes. Again using Keeney's reasoning, we suggest the utility function

$$u_t(x,y) = 0.87u_{tx}(x) + 0.13u_{ty}(y)$$

where the subscript t is for taxpayers, u_{tx} (\$6 million)=1.0 and u_{tx} (\$40 million)=0.0, as before, and $u_{ty}(y)=0.9^y$. The choice of the scaling constants 0.87 and 0.13 reflect the value judgment that the taxpayers would be willing to pay \$500,000 to save the first fatality caused by this decision, but less

for each incremental life saved.

Finally, the interpersonal comparisons of utility must be made. That is, we must identify the scaling constants λ_n, λ_e, and λ_t so that we can write the social welfare function

$$\lambda_n u_n(x,y,z) + \lambda_e u_{ey}(y) + \lambda_t u_t(x,y).$$

Suppose the decision maker feels that the employees should receive primary consideration in this analysis since their impacts are potentially more severe, and the interests of the Navy should be considered next. After some reflection, he decides to use λ_e=10, λ_u=2, and λ_t=1. Substituting these values, and simplifying, we obtain the social welfare function

$$u(x,y,z) = 1.31u_x + 11u_y(y) + 0.13u_{ty}(y) + 0.56u_z(z)$$

where $u_x(x) = 0.0$ if x=\$40 million and 1.0 if x=\$6 million,

$u_y(y) = (400-y)/y$,

$u_{ty}(y) = 0.9^y$, and

$u_z(z) = 0.0$ if z="bad," 0.75 if z="neutral," and 1.0 if z="good."

Using the data from Table 2 in Section 4.2.3, we can now calculate the expected social welfare function value for alternative Programs A and B. The calculations for Program A are shown in Table 4, with a resulting value of 11.494. In a similar manner, we can calculate the social welfare function value for Program B, and obtain 12.703. Notice that Program B is again preferred, even though this social welfare function places a much larger "weight" on fatalities (y) than the multiattribute utility function. The low probabilities associated with these risks compensate for their serious

x	y	z	u(x,y,z)	p	p·u(x,y,z)
40	0	g	(1.31)(0) + (11)(1) + (0.13)(1) + (0.56)(1) = 11.69	0.5	5.845
40	0	n	(1.31)(0) + (11)(1) + (0.13)(1) + (0.56)(0.75) = 11.55	0.2	2.310
40	0	b	(1.31)(0) + (11)(1) + (0.13)(1) + (0.56)(0) = 11.13	0.3	3.339
					11.494

Table 4. Expected Social Welfare
Calculations for Policy A

negative consequences (in this illustrative example).

4.3.4. A critique of social welfare theory. The most obvious difficulty associated with social welfare theory is the need to assess the utility functions of the different interest groups. The exhaustive identification of the relevant interest groups could be a controversial task in itself. Then, a representative of each group would be needed to express the consensus of the group preferences. In real applications, the participants in such an exercise might be tempted to alter their responses in order to influence the final outcome rather than to report their true preferences. Coalitions of groups might form to create altered responses that would generate a better solution for each member of the coalition than their independent, true responses would provide. Dyer and Miles [1976] report that this type of behavior was actually observed in their application of social welfare theory.

The idea of asking the decision maker to use "imaginative empathy" to create utility functions for each group might be a useful exercise for him. It should increase his understanding of how each interest group would be affected by the alternatives under consideration. However, it seems unlikely that an analysis based on this strategy could be made public as the basis for a decision. Interest groups not in agreement with the decision would seem likely to challenge the hypothesized representations of their preferences.

A decision maker would be placed in a difficult position if he were required to argue that he understood a group's preferences better than it did!

Another striking problem is the choice of weights for the different interest groups. These weights simultaneously reflect the relative importance of each group and some notion of each group's strength of preference for each of the alternatives. For example, if one group is roughly indifferent among all of the alternatives, but another has strong feelings about them, then the latter group should receive a large weight in the decision, ceteris paribus. There is no "objective, scientific" basis for these judgments, so the results would surely be controversial.

At a more philosophical level, this methodology also allows the "benefits" to one interest group to be traded-off against the "costs" to another. As we noted earlier, this concept has been strongly criticized by Ashford [1976, 1978] and others. To its credit, however, the method includes a mechanism to allow the introduction of judgment regarding the severity of the impacts on any group through the selection of the weights. This feature is both an advantage of the approach, and a disadvantage since the choice of the weights is virtually certain to be controversial.

5. Synthesis and Conclusions

In this section, we provide a synthesis of the methodologies of decision analysis and suggest some areas for further research. In doing so, we are led to the conclusion that these methodologies can be used to provide a richer understanding of occupational health and safety problems.

5.1 Synthesis

Throughout this report, we have pointed out some of the relationships among the methodologies of decision analysis, and we have indicated that cost/benefit analysis can also be considered a special case of decision analysis. Here we emphasize and elaborate on these points.

In Section 3.1, we identified the following five steps of decision analysis: problem definition, problem structuring, estimation of probabilities, assignment of values, and calculation. The last four of these steps may be illustrated visually, as shown in Figure 4. The tree in Figure 4 results from structuring a problem by identifying alternative decisions, events, and outcomes. The outcomes are represented by an n-dimensional vector. These outcomes are then valued, and a certainty equivalent is calculated and used to rank the alternatives.

All of the decision analysis methodologies would be applied in exactly the same manner in defining the problem, structuring the problem, and assigning probabilities to the outcomes. In risk analysis, there is more emphasis on the process of estimating the probabilities of the various outcomes, but multiattribute utility theory, social welfare theory, and cost/benefit analysis all assume that these probabilities have been determined. Further, all of these methodologies perform the calculation step in the same way, by computing the expected value of each alternative using the estimated probabilities

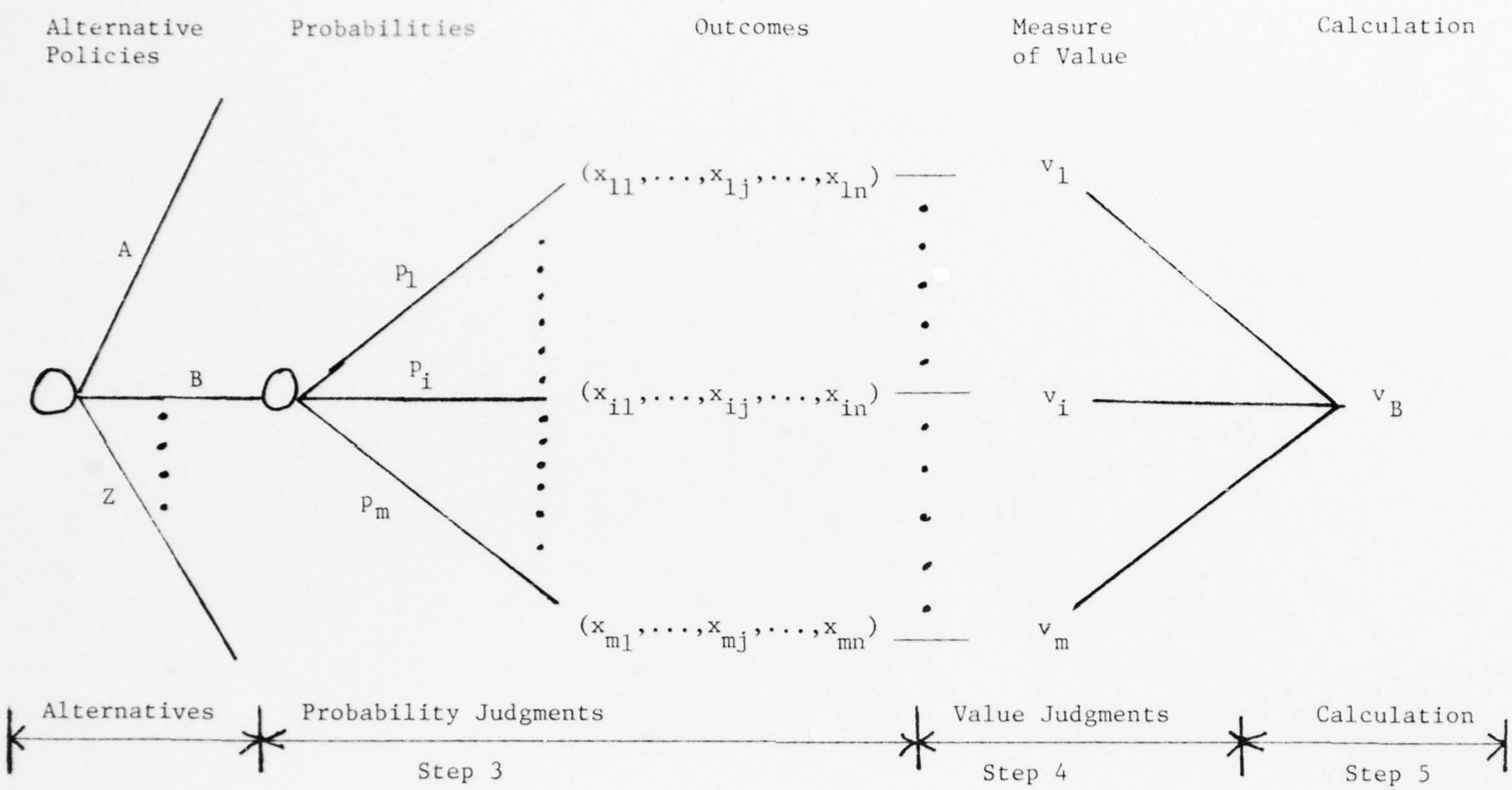

Figure 4

Evaluation of Outcomes by the Methodologies of Decision Analysis

p_i and the measures of value v_i assigned to each outcome. Therefore, the only differences among these methodologies occur in the assignment of a measure of value to each multidimensional outcome. Notice that this is the step labeled a value judgment in Figure 4.

Risk analysis focuses on estimating the probability that death or serious bodily harm will result from the choice of an alternative. Therefore, a risk analysis would let the measure of value $v_i = p'_i$, where p'_i is calculated by multiplying the probability that an outcome will occur p_i times the number of people that would be killed, and dividing by the size of the relevant population. A risk/benefit analysis would let $v_i = (p'_i, b_i)$, where b_i is the net monetary value of the non-risk costs and benefits associated with an outcome. Generally, there is no explicit attempt to trade off p'_i and b_i so that v_i can be reduced to a scalor. The advantage of this approach is that both the estimation of the probabilities p'_i and of the net benefits b_i can be considered to be objective, and based on scientific principles. The disadvantage is that no unique ranking of the alternatives will result, since the ranking will depend on the trade-off between risk and the monetary estimates of the net non-risks costs and benefits.

When multiattribute utility theory is applied to the problem, $v_i = u\ (x_{i1},\ldots,x_{in})$, where u is a multiattribute utility function. Since some x_{ij} may measure deaths and another may be monetary costs, this approach does require an explicit trade-off between risks (or a human life) and monetary costs. It is also possible to add other factors in the analysis that can only be estimated subjectively, such as the impact of a decision on the image of an organization. The advantages of this approach are that it can more accurately represent the true preferences of the decision maker, and

that it does lead to an unambiguous ranking of alternatives. The disadvantage is that it requires explicit value judgments, so reasonable men may disagree over these judgments and the rankings that result.

Notice that _if_ a constant trade-off rate w between risks and benefits could be obtained, then we could let

$$v_i = u(p_i', b_i) = wp_i' + b_i$$

so that risk/benefit analysis would become a special case of multiattribute utility theory.

When social welfare theory is applied, $v_i = w\,(u_1(x_{i1},\ldots,x_{in}),\ldots, u_k(x_{i1},\ldots,x_{in}),\ldots)$ where w is the social welfare function and u_k is the utility function of the _kth_ individual in society. Often individuals will be members of special interest groups that are assumed to have similar preferences, so that u_k would represent the preferences of the _kth_ group. Further, each interest group may be concerned with only a small subset of the outcomes, perhaps only one. When this occurs, the resulting social welfare function w may be indistinguishable in form from a multiattribute utility function, except each attribute is valued by one or more groups rather than by a single decision maker. The advantage of this approach is that it explicitly recognizes the preferences of the diverse groups that are concerned about the choice of a policy. The disadvantage is that it is difficult to operationalize, since we must obtain utility functions from each interest group and explicitly trade-off among them.

As we have noted in Section 4.3.1, if we impute a market value for all of the outcomes x_{ij}, if we assume that each individual values these outcomes at their market values, and if we assume that the value of an additional dollar is constant and equal among all individuals, then the

application of social welfare theory is the same as the use of cost/benefit analysis. Further, if we assign a monetary value to human life, then we can obtain a trade-off rate w' between the probability that an individual will be killed and the monetary benefits of a project. Therefore, we could convert a risk/benefit analysis into a cost/benefit analysis by letting

$$v_i = w'p_i' + b_i$$

Notice, however, that this is precisely the form of the expression that we introduced to argue that risk/benefit analysis was a special case of multiattribute utility theory, except that we have specified the basis for estimating w'.

The approaches for valuing outcomes are summarized in Table 5. As we have seen, by making a series of restrictive assumptions, each of these three methodologies of decision theory can be made equivalent to cost/benefit analysis, and therefore to each other. This does not mean that all four methods are identical, but simply emphasizes that the basis for valuing outcomes is the only distinguishing feature of them.

Method	Evaluation of Outcomes
Risk/Benefit Analysis	Estimate the probability of death (or other harm) and the net non-risk, monetary costs and benefits. The result is a two dimensional vector.
Multiattribute Utility Theory	Create a utility scale for each criterion and aggregate the scales. The result is a scalor.
Social Welfare Theory	Create a utility scale for each individual and aggregate the scales. The result is a scalor.
Cost/Benefit Analysis	Transform all outcomes into dollars using actual or imputed market values. The result is a scalor.

Table 5

Evaluation of Outcomes by the Methodologies of Decision Analysis

5.2 Suggestions for Research

The methodologies of decision analysis show great promise as an aid in the management of the occupational health and safety programs of the U.S. Navy. Given the current state-of-the-art in the field of decision analysis, we are convinced that these methodologies could be successfully applied to a variety of problems. Nevertheless, there are areas where further research could improve the practical potential of these decision aids.

The first area would involve fundamental research on the meaning of the term "risk" and how it affects an individual's preferences. As we have noted, the concept of risk is ambiguous, and its role in decision making is not well understood. The von Neumann-Morgenstern utility function confounds an individual's strength of preference for outcomes and his attitude toward risk. Dyer and Sarin [1978b] have suggested decomposing this function into these two component parts as a means of analyzing the impact of a risk attitude on decision making. This research may eventually lead to a deeper understanding of how people are influenced by risk, and to a sounder basis for hypothesizing that alternative forms of utility functions are appropriate to represent an individual's preferences. It also seems likely that new assessment techniques will result from this work. Since the issue of risk is fundamental in occupational health and safety, we feel that work along these lines should be encouraged.

Other work related to the issue of risk might be an extension of Keeney's research on public risk and on the evaluation of alternatives involving potential fatalities (Keeney [1978a, 1978b]). He argues for specific forms

of the multiattribute utility function that would be appropriate for evaluating alternatives in occupational health and safety. Once the appropriate form of a utility function has been determined, a parametric analysis can often be used to eliminate a large number of alternatives without requiring the decision maker to express his preferences.

The second area of potentially fruitful research would explore the sensitivity of the results of a decision analysis to changes in the form and the parameters of a utility function or a social welfare function. As we have seen, both Maurer [1977] and von Winterfeldt [1978] have obtained useful insights into problems by hypothesizing the form of a function and performing a parametric analysis. What if we also change the form of the utility function, from additive to multiplicative, for example? A decision analysis based on a single assessed utility function or social welfare function can always be criticized on the grounds that the function might be only a crude approximation to true preferences. Further work in this area might help to alleviate this problem.

Again, a related effort is work by Sarin [1978b] that requires only bounds on estimates of utility function parameters and on probabilities in order to eliminate alternatives. In many real-world applications, a decision maker may hesitate to provide exact values for trade-off rates among criteria, or exact values for probabilities. As Sarin has shown, however, rather loose bounds on these values can often be sufficient to identify the preferred alternative.

The third and final area for additional research would involve actual applications of decision analysis to significant, real-world problems. These initial applications would actually be valid research in the sense that more work would be required on the task of defining and structuring occupational

health and safety problems. Relevant outcomes for the analysis would also have to be identified. Methods for estimating probabilities would need to be developed. Finally, an actual application would provide a useful testing ground for the ideas generated by research in the first two areas that we identified.

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